SHOCK PROPAGATION RESPONSE OF COMPOSITE LATTICE STRUCTURES

K. Shimode[a*], T. Yokozeki[a], T. Aoki[a], K. Terashima[b], T. Kamita[b]

[a]*Department of Aeronautics and Astronautics, University of Tokyo, : 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654 Japan*
[b]*Japan Aerospace Exploration Agency, 1-1 Sengen 2chome, Tsukuba-shi, Ibaraki 305-8505*
**shimode@aastr.t.u-tokyo.ac.jp*

Keywords: CFRP, wave propagation, lattice structure, impact experiment

Abstract
Anisogrid lattice structure, consisting of helical and hoop ribs intersecting each other in a regular pattern, is considered to be a superior candidate as the lightweight aerospace structure such as payload attachment adapter and inter-stage structure of launch vehicles. Owing to the nodal structure, it is also expected that lattice structure has high wave attenuation and vibration damping properties. In this study, composite lattice structure fabricated by low-cost process is focused on, and its shock propagation behavior is experimentally evaluated. It is concluded that composite lattice structure exhibits high wave attenuation properties in terms of Frequency Response Function (FRF) and Shock Response Spectrum (SRS) compared to conventional structures.

1. Introduction

Anisogrid lattice structure is the structural concept consisting of helical and hoop ribs intersecting each other in a regular pattern. Because of its high structural efficiency, lattice structure is considered to be a superior candidate as the light-weight aerospace structure such as payload attachment adapter and inter-stage structure of launch vehicles. A number of studies have been conducted on CFRP anisogrid lattice structure in Russia. According to Vasiliev [1], wide application of anisogrid lattice structures have been found in the Russian heavy space launcher Proton-M. Application of these structures has resulted in considerable reduction of the rocket mass and the corresponding increase of the payload weight. Recently, composite lattice structures receive much attention as light-weight aerospace structures, specifically in Europe [2,3]. Japan Aerospace Exploration Agency is also investigating applicability of CFRP lattice structure to the structures of space launcher [4,5].

It is also expected that lattice structure has effect of damping these loads owing to the nodal structure. Spacecraft, payloads and their components experience severe high-level shock and loads during separation from launch vehicle, deployment of the solar array panel and instruments, etc. Pyrotechnic device is widely employed in space vehicle separation, deployment of solar array panel and release of constrain [6]. These kinds of pyrotechnic shock devices produce transient loads with high levels of acceleration in different location of satellite. In the earlier design of spacecraft, it is necessary to decide the shock response spectrum (SRS) environment interface limitations for the payload. NASA publish the empirical curve that predicts SRS interface limitation [7]. Studies on shock propagation behavior of lattice structures have been rarely performed, while Nishida et al. measured transient responses to impact of impulse hammer in isogrid lattice structure [8]. CFRP lattice structure fabricated by low-cost process is focused on, and its shock propagation behavior is experimentally evaluated in this study. Transient responses of CFRP lattice structure by the impact of impulse hammer are measured using accelerometers. The obtained responses are analyzed by the scaled SRS and Frequency Response Function (FRF) as a function of the distance of measurement location from the source. The wave attenuation properties of several structures including composite lattice structure are compared

2. Experiment

2.1. Materials and Specimens

The experiment was performed for beam structure with periodic nodes (Figure 1), and beam structure without nodes (Figure 1), cylindrical lattice structure (Figure 2), plate-like lattice structure (Figure 2). The plate-like lattice structure and the beam structure were cut from the cylindrical lattice structure, and these specimens cover multiple units of the anisogrid. The material system was carbon fiber/epoxy resin composite. Beam structure without nodes was not cut from lattice structure, but from CFRP plate (carbon fiber/epoxy resin) for comparison. 38 fiber layers were laid up at the intersections of helical and hoop ribs, whereas 19 layers were laid up in the general sections of ribs. The composite lattice structures were fabricated using the semi-automated wet winding process. The properties of CFRP lattice structure were summarized in Table 1 [5] and Table 2. The definition of these properties is shown in Figure. 2.

Number of hoop ribs Ne	15
Number of helical ribs Nh	71
Helical rib angle Φ	21.4 deg
Width of hoop ribs bc	5.7 mm
Width of helical ribs bh	4.7 mm
Rib thickness H	10 mm

Table 1. Properties of Cylindrical Lattice Structure and Plate-Like Structure

Rib thickness H	11 mm
Width of Ribs b	3.5 mm
Young Modulus of the parts between Intersections E	84.7 GPa
Poisson Ratio of the parts between	0.35

Table 2. Properties of Beam Structure without Nodes

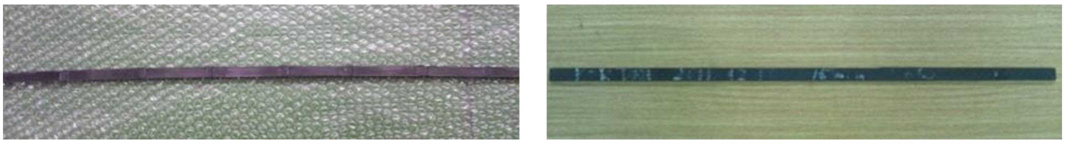


Figure 1. Left: Beam Structure with Nodes (Length: 200 mm), Right: CFRP Beam Structure without Nodes (Length: 200 mm)

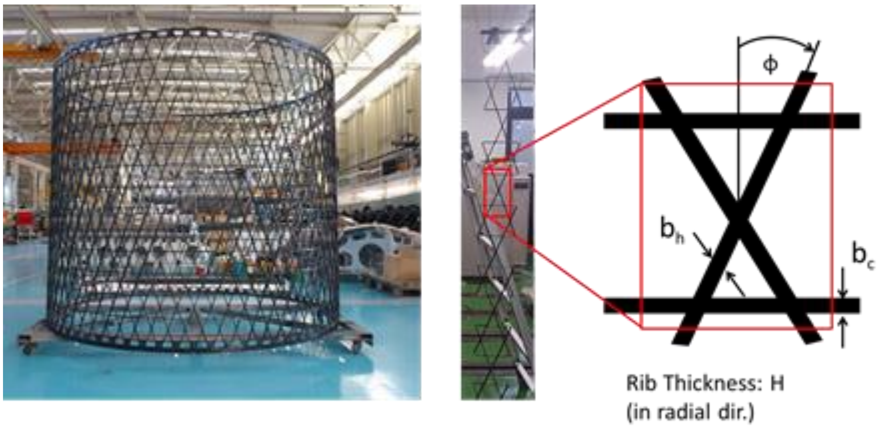


Figure 2. Left: Cylindrical Lattice Structure (Height: 2000 mm), Right: Plate-Like Lattice (Height: 2000 mm)

2.2. Experimental Procedure

Transient responses of specimens excited by the impact using impulse hammer (Onosokki: GK-3100) were measured by accelerometers (PCB: 353B15). We attached metal tip to the impulse hammer in order to input high frequency shock waves. Impact loads were applied over 20 times, and the measurement data were averaged. We dangled specimens with strings to avoid influence of mechanical constraints in the measurements of beam structure, while large-scale cylindrical structure and plate-like structure were clamped at the lower end. The longitudinal waves and flexural waves are measured by the accelerometers for all cases. The orientation of these waves is shown in Figure 3. Transient responses were recorded as a function of the distance from the impact point, and the sampling frequency was 1 MHz. For example, the measured points for cylindrical lattice structure and plate-like structure are shown in Figure 4. In the both measurements, two accelerometers were attached on helical ribs, and their data were averaged.

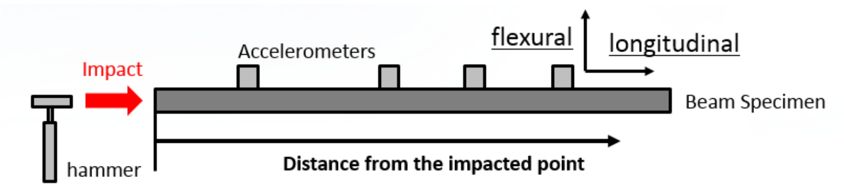


Figure 3. Measured Points for Plate-Like Structure

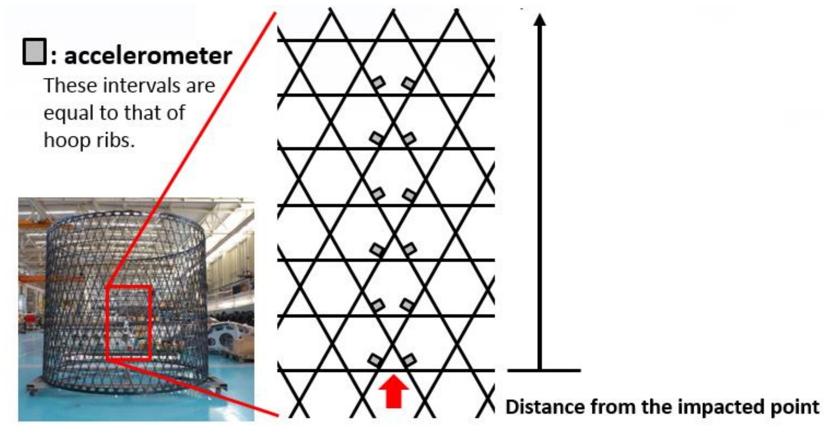


Figure 4. Measured Points for Plate-Like Structure

2.3. Data Analysis

We used Frequency Response Function (FRF) and Shock Response Spectrum (SRS) for data analysis. We can evaluate wave attenuation in the frequency domain and predict response in an optional point in structure with FRF. SRS is widely used to scale pyroshock environment.

FRF can be written as

$$\mathrm{G}(\omega) = \frac{\overline{F(\omega)}X(\omega)}{\overline{F(\omega)}F(\omega)} = \frac{W_{fx}(\omega)}{W_{ff}(\omega)} \tag{1}$$

where F (ω) is complex Fourier transformation of input force history, f (t), and X (ω) is complex Fourier transformation of measured output, x (t). The superior bar means conjugate of the complex number. In the present data analysis, measured data of impulse hammer and accelerometers at several locations were converted to the frequency domain from the time domain by Fast Fourier Transform (FFT). In this research, responses in measured points are compared with the response at the nearest point from the impact point. Therefore, transmittance of wave propagation is defined as

$$\alpha_i = \frac{|G_i(\omega)|}{|G_0(\omega)|} \tag{2}$$

where “i” is the number of measured point, and “0” denotes the nearest point. Hence, the less transmittance means more attenuation of the magnitude of the response. We decided effective measurement range by power spectrum (the denominator of FRF) of input. The effective measurement range was less than 5 kHz from that.

SRS is a calculated function based on the acceleration time history [9]. It applies an acceleration time history as a base excitation to an array of single-degree-of-freedom (SDOF) systems having each natural frequency. In this study, the damping of each system was set to be 5%, and the base input were the transient responses of the measured accelerations. The SRS is the peak absolute acceleration response of each SDOF system to the time history base input. Moreover, the transmittance of wave propagation in terms of SRS is defined in this study as

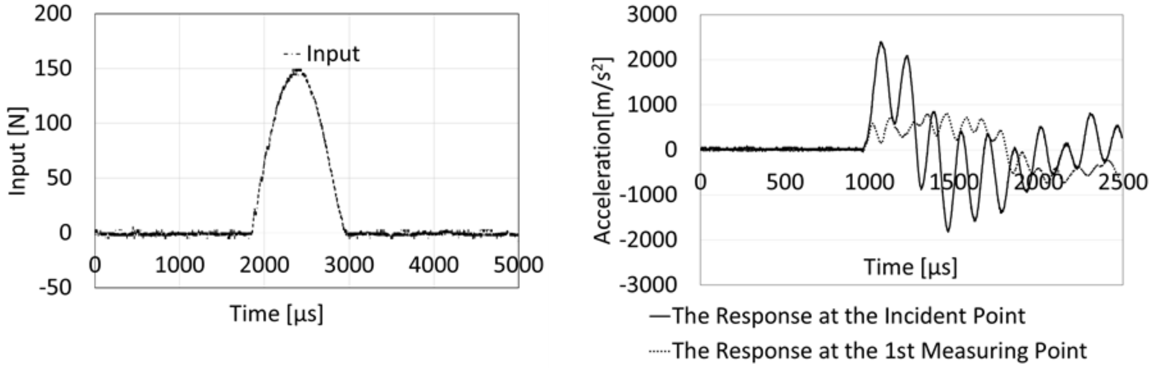
$$\alpha_i = \frac{SRS_i(f_n)}{SRS_0(f_n)} \tag{3}$$

Peak values of inputs and responses were also measured, and peak responses normalized by the input’s peak force are called peak ratio in this study. Transmittances of these peak ratios are defined similarly.

3. Results

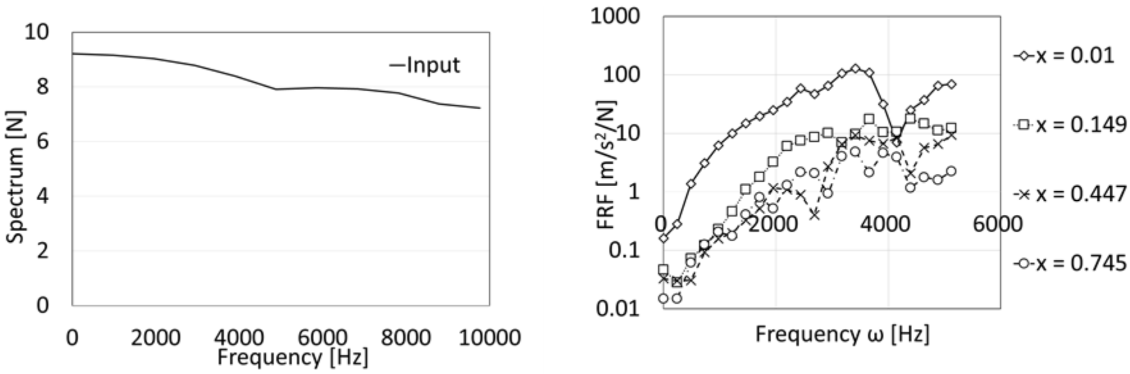
3.1. Wave Attenuation in FRF

Examples of the time history of impact input and accelerometer response are shown in Figure 5. FRF of the impact input signal is depicted in Figure 6(a), indicating that the frequency range of the impact input reaches 5 kHz. FRFs of the measured accelerations, which were calculated by equation (1), are presented in Figure 6(b). The transmittance in FRF of longitudinal waves in beam structures at the frequency of 1 and 2 kHz is summarized as a function of the distance between the impact point and the accelerometer locations, as shown in Figure 7. The abscissa of these graphs is the distance of the measured location from the impacted point, and the ordinate represents the transmittance. The transmittance of wave for beam structure with nodes is less than that for beam structure without nodes in 1 kHz and 2 kHz. Figure 8 depicts the transmittance of flexural wave in cylindrical structure. The transient responses attenuate as the stress wave propagates in all frequencies for cylindrical structure. In particular, the transmittances are lower than 20% after propagating 3 units from the impact point.



(a) Impact Input (b) Accelerometer response

Figure 5. Time history of impact input and received wave



(a) Impact input spectrum (b) FRF at several locations of cylindrical structure

Figure 6. Spectrum of impact force and example of evaluated FRFs

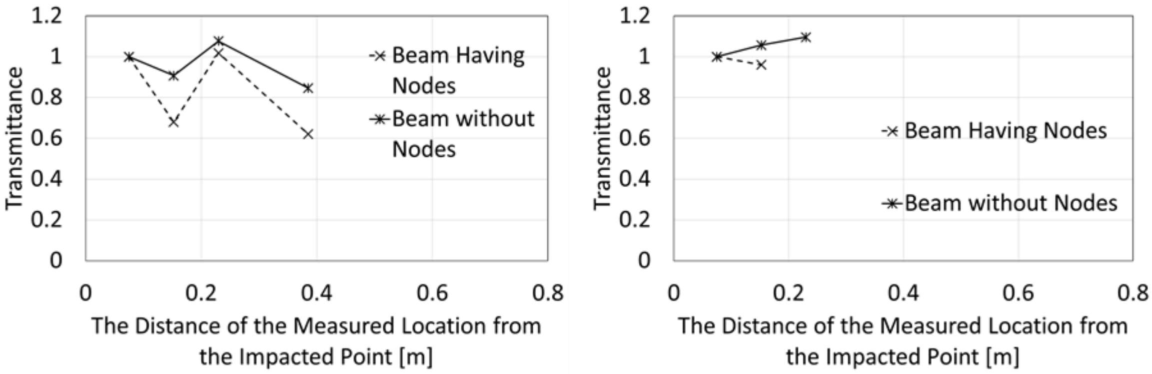


Figure 7. FRF Transmittance for Beam Having Nodes and without Nodes (Left: 1 kHz, Right: 2 kHz).

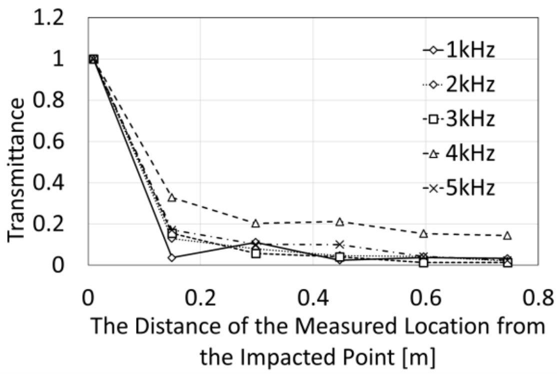


Figure 8. FRF Transmittance for Cylindrical Structure

3.2. Wave Attenuation in SRS

The transmittance in SRS for each specimen at the frequency of 1 and 2 kHz are shown in Figure 9. The abscissa of these graphs is the distance of the measured location from the impacted point. The graph named "NASA" is drawn by approximate curve from the shock response spectrum measured in the reference [10]. This response was produced by point pyroshock sources in complex structures. The longitudinal wave and the flexural wave for the plate-like structure and cylindrical structure attenuate as the stress wave propagates in frequencies of 1 kHz and 2 kHz, and similar tendencies are also confirmed in 3 kHz, 4 kHz and 5 kHz. On the other hand, the attenuation is lower in 1 kHz than in higher frequencies for the plate-like structure.

3.3. Wave Attenuation of the peak values

The peak acceleration normalized by the input peak was defined as "peak ratio" in this study to eliminate influence of variation in the input power. The transmittance of the peak ratio for each specimens are shown in Figure 10. The abscissa of the graph is the distance of the measured location from the impacted point. The graph named "Honeycomb" and "Complex airframe" are sets of the scaling curves for typical pyroshocks propagating through various types of structure developed by Kacena and Others [10]. The results were obtained from the peak value of the pyro shock response in time domain. Reference [10] indicated that honeycomb structure exhibited the highest transmittance (i.e. the lowest attenuation), while the complex airframes (e.g. longeron or stringer, primary truss members, cylindrical shell, ring frame, and complex equipment mounting structure) exhibited the lowest transmittance. Figure 10 demonstrates that lattice composite structure exhibit superior shock attenuation in terms of the peak ratio.

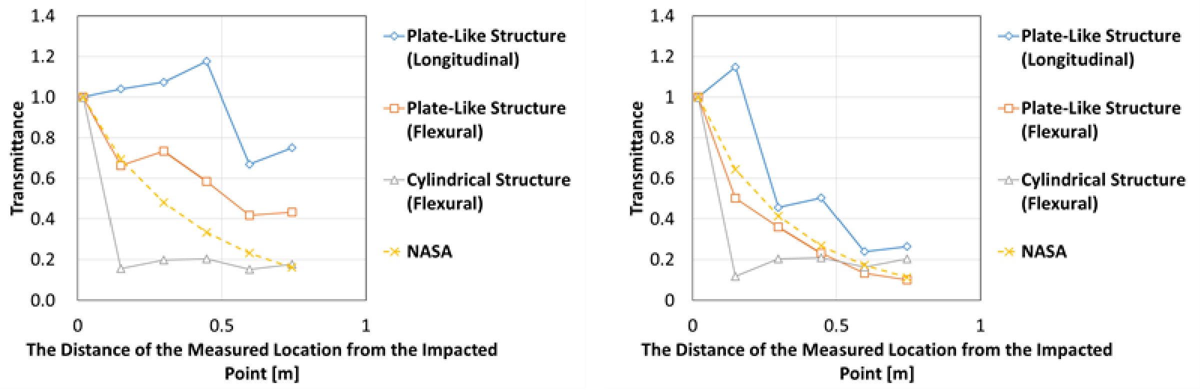


Figure 9. SRS Transmittances (Left: 1 kHz (a), Right: 2 kHz (b))

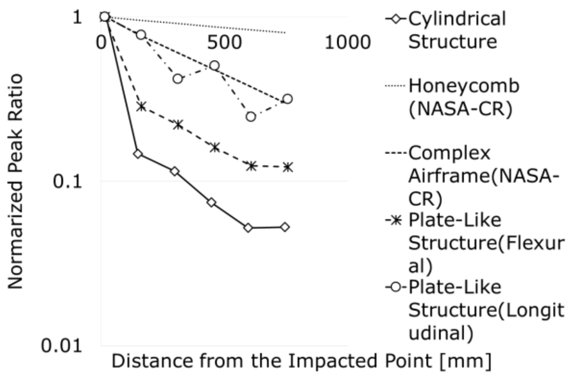


Figure 10. Peak Ratio Transmittance

4. Discussion

The transmittances of wave in beam structure with periodic nodes are less than that in beam structure without nodes as shown in Figure 7. It can be concluded that the nodal structure contributes to wave attenuation.

The transmittances of the lattice cylindrical structure are lower than that of the other structures as depicted in the Figure 9 and Figure 10. Although there remain discussions on scatters and measurement methods, the damping effect for the transient responses in the composite lattice cylindrical structure is significant compared to the conventional structures.

Attenuations of transient responses were smaller for 1 kHz in SRS of the plate-like structure. It depends on frequency whether the wave attenuates or not. The SRSs for the longitudinal wave and flexural wave of the plate-like structure are shown in Figure. 11, and the abscissa of these graphs is frequency, and the ordinate represents the SRS. SRSs at 758 mm (5 Unit propagated) have slopes and plateau regions with peaks at specific frequencies in these graphs. The transient response attenuates as distance in frequencies over the above-mentioned specific frequencies. This peak frequency is called as knee frequency, and it is known as the major local structural frequency. Therefore, whether the wave attenuate or not is likely to depend on natural frequency of the structure related to vibration. It is also said that the larger specimen becomes, the less the responses exhibit in Figure 9 and 10, even when the distance from the impact point is same. Hence, the magnitude of the response of measured points also depends on the scale of specimen, owing to, namely, spatial spreading of the stress wave. Waves are attenuated by the special spreading effects, energy dissipation effects of the material and the reflection effects at the intersections of the specimens from above results. On the other hand, mode vibrations prevents attenuation of the waves at the natural frequencies.

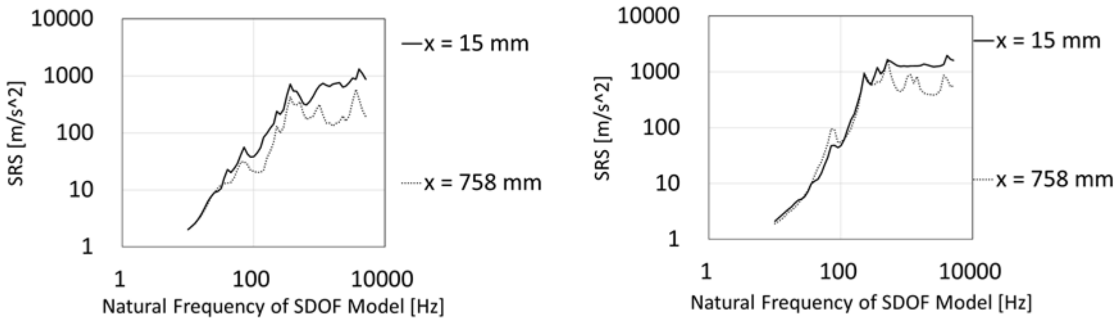


Figure 11. SRSs of the Plate-Like Structure (Left: Longitudinal Wave, Right: Flexural Wave)

5. Conclusion

CFRP lattice structure was focused on in this study, and its shock propagation behavior was experimentally evaluated and analyzed using FRF and SRS. It was shown that the nodal structure contributes to wave attenuation. Moreover, we compared the measured transmittance of lattice cylindrical structure with other structures from the literature. It was demonstrated that the damping effect for the transient response in the composite lattice cylindrical structure is more significant compared to the conventional structures.

References

[1] V. V. Vasiliev, V. A. Barynin, and A. F. Razin. Anisogrid composite lattice structures–development and aerospace applications. *Composite structures*, Vol. 94(3), pp 1117-1127, 2012.
[2] G. Totaro and Z. Gürdal. Optimal design of composite lattice shell structures for aerospace applications. *Aerospace Science and Technology*, Vol. 13(4), pp 157-164, 2009.
[3] G. Totaro. Local buckling modelling of isogrid and anisogrid lattice cylindrical shells with triangular cells. *Composite Structures*, Vol. 94(2), pp 446-452, 2012.
[4] T. Aoki, T. Yokozeki, K. Terashima and T. Keita. Mechanical Behavior of Composite Lattice Cylinders. In *55th AIAA/ASMe/ASCE/AHS/SC Structures, Structural Dynamics, and Materials Conference*, American Institute of Aeronautics and Astronautics. doi:doi:10.2514/6.2014-1061, 2014
[5] K. Terashima, T. Kamita, G. Kimura, T. Uzawa, T. Aoki and T. Yokozeki. Experimental and analytical study of composite lattice structure for future Japanese launcher. *Proceedings of ICCM-19*, 2013, USB.
[6] S. Qinzhong, et al. The summarization of pyro-shock testing data and SRS level prediction methodology. *Environmental Testing for Space Programmes*, Vol. 558, pp 549-554, 2004.
[7] Mulville. Daniel R. Pyroshock *Test Criteria, NASA Technical Standard. Report NASA-STD-7003*, 1999.
[8] A. Nishida and K. Kawaguchi. Experimental Studies on Wave Propagation Behavior of Lattice Structures. *.J. Struct. Constr. Eng., AIJ,* Vol. 597, pp 69–76, 2005.
[9] T. Irvine. An introduction to the shock response spectrum. *Revision M*, 2002.
[10] W. J. Kacena, M. B. McGrath and W. P. Rader. Aerospace Systems Pyrotechnic Shock Data. *NASA Contractor Report*, 116437, 116450, and 116401, 1970.